

Tevatron measurements on Standard Model Higgs

49th Rencontres de Moriond
Electroweak Interactions and Unified Theories

Federico Sforza
on behalf of the CDF and D0 Collaborations

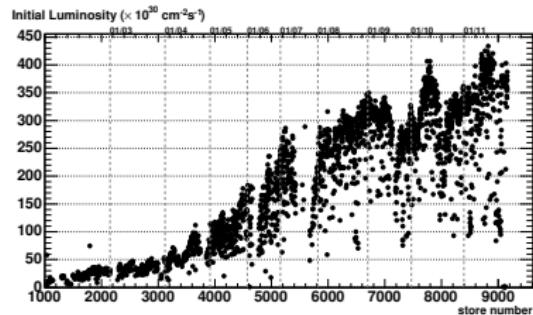
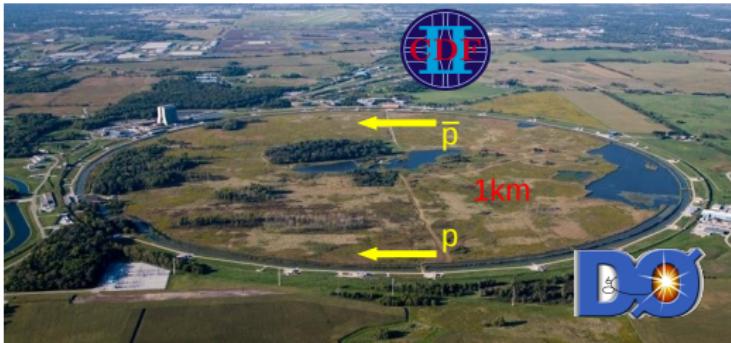
Max Planck Institut für Physik

20th March 2014 - La Thuile

The Tevatron

Presented analyses use full Run II dataset:

Up to $\int \mathcal{L} \simeq 10 \text{ fb}^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96 \text{ TeV}$ per experiment ($\simeq 12 \text{ fb}^{-1}$ delivered)

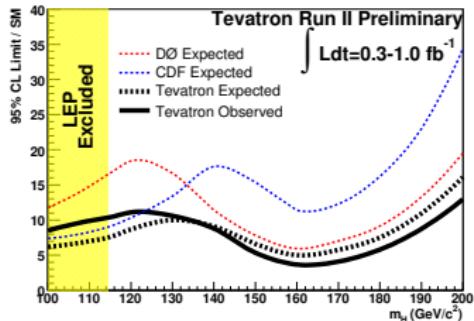


Store initial luminosity $\times 20$ increase over years
 ⇒ driven by abundance of anti-protons

Tevatron facts:

- Two instrumented collision points: **CDF & D0** experiments
- First superconducting accelerator and largest *anti-matter* source in the world
- Run I and Run II cover almost 20 years of physics

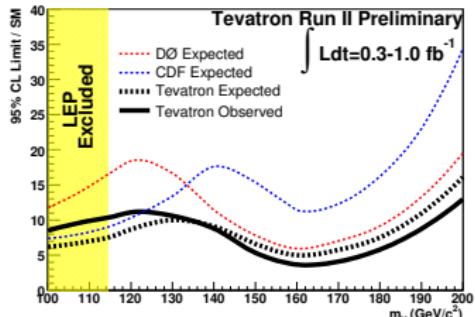
A Very Brief History of Higgs Searches



Tevatron role was unexpected several years ago:

- First Tevatron combination for SM Higgs 95% C.L.:
 $\Rightarrow 2006, 0.3 - 1 \text{ fb}^{-1}$ ([CDF 8384 & D0 5227 Notes](#))
- 95% exclusion sensitivity $\mathcal{O}(10) \times \text{SM}$
- 100 fb^{-1} needed to reach 2σ sensitivity!

A Very Brief History of Higgs Searches

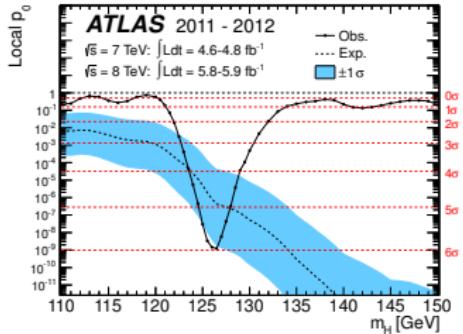


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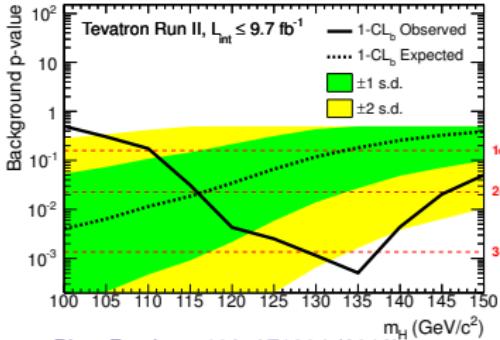
The July 2012 discovery of a new particle compatible with SM Higgs ($m_H \approx 125 \text{ GeV}/c^2$):

ATLAS, CMS observation in $4\ell, \gamma\gamma$ final states:



Phys. Lett. B 716 (2012) 1 and 30

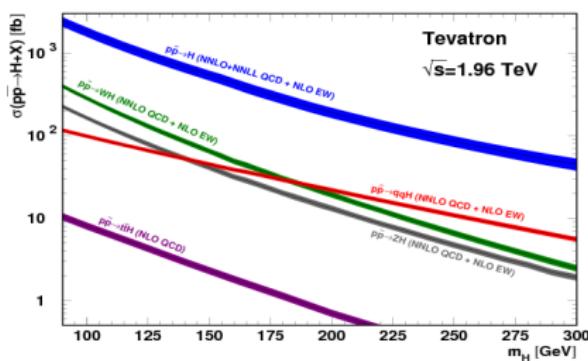
Tevatron evidence in $b\bar{b}$ final state:



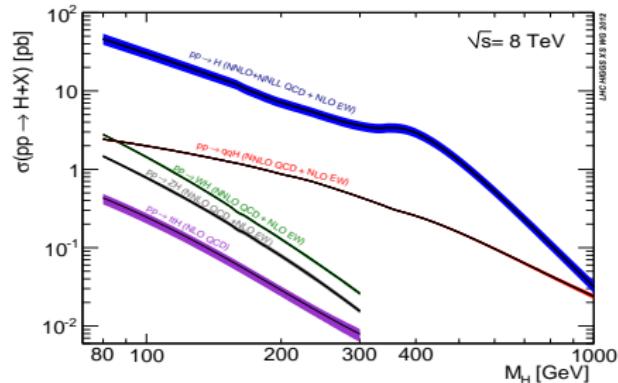
Phys. Rev. Lett. 109, 071804 (2012)

Higgs Production Mode Differences at Tevatron and LHC

Tevatron Higgs production modes (1.96 TeV):

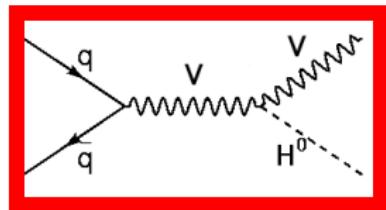


LHC Higgs production modes (8 TeV):

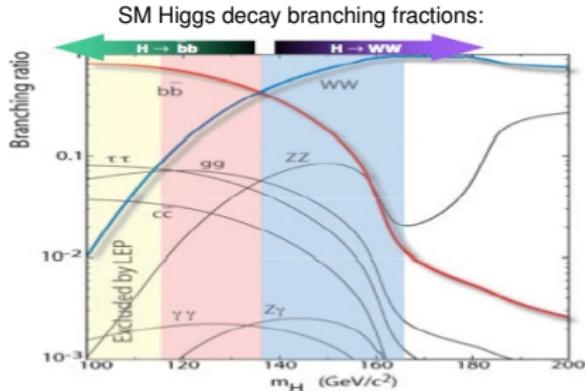


Higgs production rate at LHC much higher than at Tevatron:

- LHC gluon fusion $\times 20$, Vector Boson Fusion (VBF) $\times 30$
 - \Rightarrow Abundant production modes for analysis of clean final states with small BR ($\gamma\gamma$, ZZ , WW , $\tau\tau$)
- LHC VH associate production $\times 4$, also higher background:
 - \Rightarrow *Relevant and complementary studies from Tevatron!*



Analysis Classification



High Mass:

- High BR final states for $m_H \gtrsim 135 \text{ GeV}/c^2$
- Main channel: $gg \rightarrow H \rightarrow WW$
- $WW \rightarrow \ell\nu\ell\nu$: low background
- High Higgs production rate

Low Mass:

- High BR final states for $m_H \lesssim 135 \text{ GeV}/c^2$
- main channel: $qq \rightarrow VH \rightarrow b\bar{b}$
- V leptonic decay: online selection and background reduction

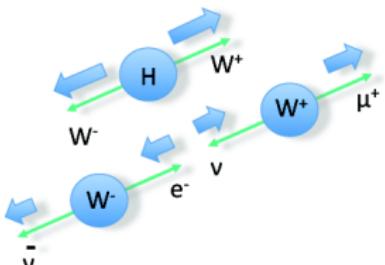
Peculiarity of $m_H = 125 \text{ GeV}/c^2$: $BR(H \rightarrow b\bar{b}) \simeq 0.58$, $BR(H \rightarrow WW) \simeq 0.21$

⇒ Both low and high mass analyses contribute to properties study

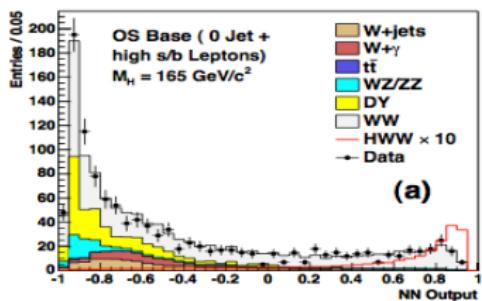
Overview of $H \rightarrow WW$ Analysis

- Lepton plus E_T selection (also hadronic τ):
 ⇒ *s/b* event categorization to enhance sensitivity
- Low Higgs mass resolution because of 2ν
- Lepton kinematic correlation for MVA discriminants:
 ⇒ Boosted Decision Trees (BDT), usually for D0
 ⇒ Neural Networks (NN), usually for CDF

Different di-lepton kinematic of $H \rightarrow WW$ decay and WW EWK production (background):

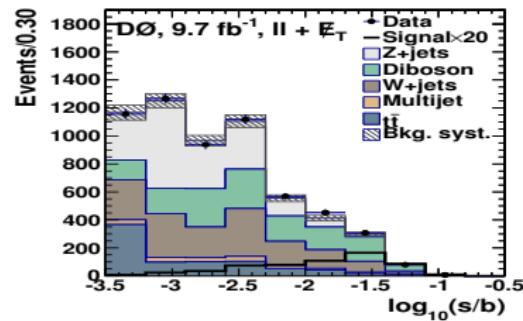


Example of CDF $H \rightarrow WW$ NN output:



Phys. Rev. D 88, 052012 (2013)

Example of D0 $H \rightarrow WW$ BDT output:



Phys. Rev. D 88, 052006 (2013)

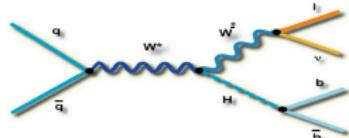
2008: first post LEP analysis to exclude presence SM Higgs boson in mass range

Overview of Low Mass Higgs Analyses

$VH \rightarrow b\bar{b}$ is the most sensitive channel at Tevatron:

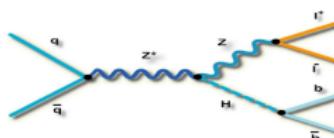
3 analyses with similar topology: leptons (charged or neutral) + heavy flavor jets

$$p\bar{p} \rightarrow WH \rightarrow \ell\nu + b\bar{b}$$



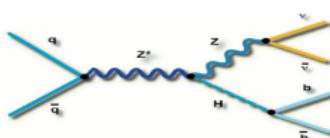
CDF: Phys.Rev.Lett. 109, 111804 (2012),
 D0: Phys.Rev.Lett. 109, 121804 (2012),
 Phys.Rev.D. 88, 052008 (2013)

$$p\bar{p} \rightarrow ZH \rightarrow \ell\ell + b\bar{b}$$



CDF: Phys.Rev.Lett. 109, 111803 (2012),
 D0: Phys. Rev. Lett. 109, 121803 (2012),
 Phys.Rev.D. 88, 052010 (2013)

$$p\bar{p} \rightarrow VH \rightarrow \nu\bar{\nu}(\nu\ell) + b\bar{b}$$



CDF: Phys.Rev.D 87, 052008 (2013),
 D0: Phys.Lett.B 716, 285 (2012)

- Similar background sources, different relative fractions between final states
- Aim to identify Higgs $M_{b\bar{b}}$ resonance over falling background
- Background estimate with mixture of MC/data driven extraction from Control Regions (CR)

Backgrounds	Shape	Normalization
$WW, WZ, ZZ, t\bar{t}$, single-top	MC based	NLO,NNLO (Theory)
Multi-Jet (MJ)	Data driven	Fit to data
$W/Z +$ light flavor	MC (ALPGEN), CR weighted	data CR
$W/Z +$ heavy flavor	MC based (ALPGEN)	LO, fit to data

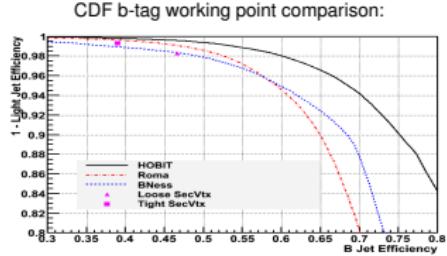
Statistically limited dataset \Rightarrow Relax cuts \Rightarrow Keep background under control \Rightarrow Iterate

Low Mass Searches Optimization

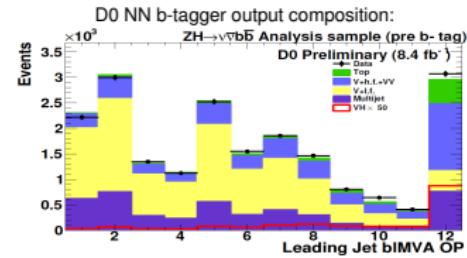
Every aspect of analyses thoroughly optimized (often using MVA):

- Inclusive trigger strategy: single lepton, only \cancel{E}_T , multiple objects ($\cancel{E}_T + \text{jets}$)
- Improved ℓ/\cancel{E}_T offline ID: relaxed cuts increases MJ \Rightarrow improve lepton ID/MJ-rejection
- b-tag: reduce background to 1/100 but limits jet selection efficiency ($\simeq 50\%$)
- Final Discriminant: large irreducible backgrounds \Rightarrow MVA sensitivity increase by 10-20%

- MVA b-tagging for both D0 and CDF
- Tunable efficiency/contamination working point
- Maximize significance from s/b categorization of signal region

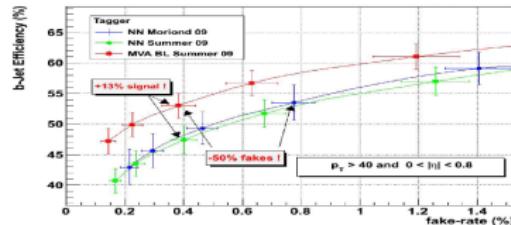


J. Freeman et al., Nucl.Instrum.Methods Phys.Res., Sect. A 697, 64 (2013)



V. M. Abazov et al., Nucl.Instrum.Methods Phys.Res., Sect. A 620, 490 (2010)

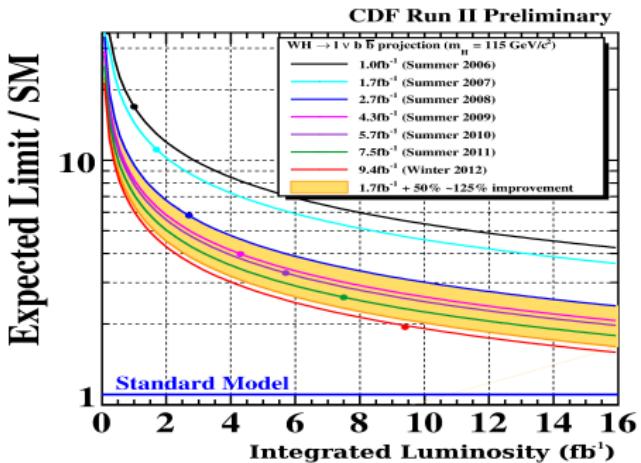
D0 b-tag algorithm improvements and working points:



Low Mass Searches Optimization

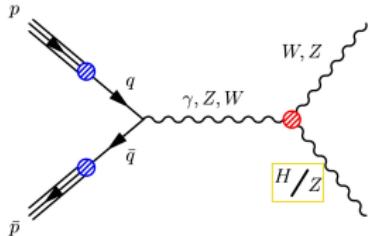
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Single channel sensitivity improvements w.r.t. 1 fb $^{-1}$ analysis was also > 200% (over luminosity)!

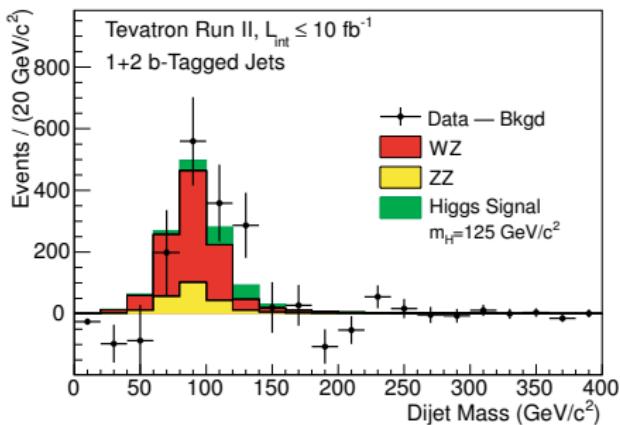
Analysis Validation with $VZ \rightarrow HF$



- Important analysis validation using known SM process as signal
- VZ associate production in s -channel with $Z \rightarrow b\bar{b}$ mimics $VH \rightarrow b\bar{b}$ signature
- $\sigma_{VZ} \times BR(Z \rightarrow HF)$ about 6 times VH ($M_H = 125$)
- Higher background due to $W+jets$ M_{jj} spectrum
 \Rightarrow very small s/b and challenging measurement!

$WZ \rightarrow HF$ evidence

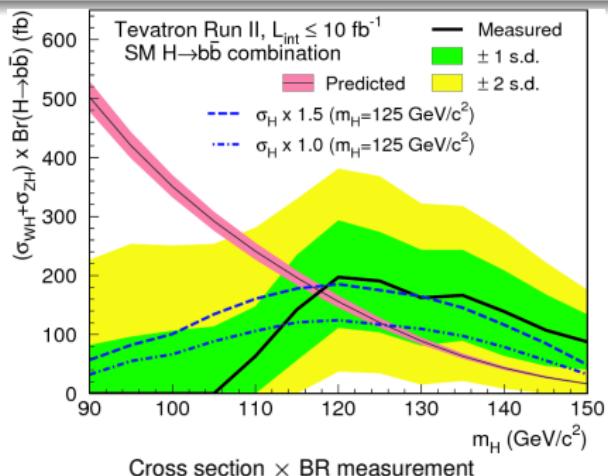
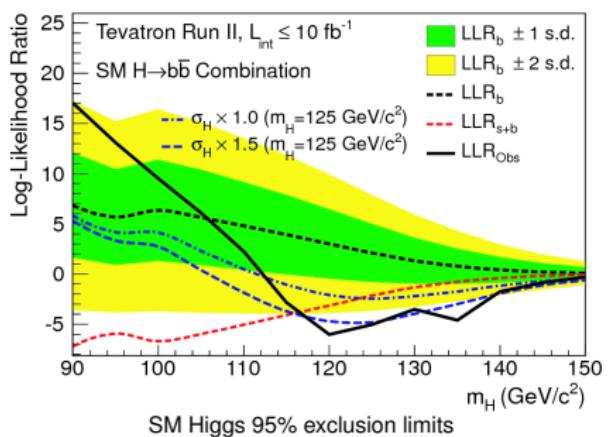
- CDF and D0 low mass analyses combined looking at $VZ \rightarrow HF$ signal
 - Same data-set, analysis techniques, MVA discriminant strategy
- $\Rightarrow \sigma_{VZ} = 3.0 \pm 0.6(\text{stat}) \pm 0.7(\text{syst}) \text{ pb}$
 \Rightarrow Strong signal evidence at 4.6σ
 \Rightarrow Consistent with $\sigma_{VZ}^{SM, NLO} = 4.4 \pm 0.3 \text{ pb}$



Background subtracted di-jet invariant mass

$H \rightarrow b\bar{b}$ Results

- Phys.Rev.Lett. 109, 071804 (2012): $H \rightarrow b\bar{b}$ low mass VH Tevatron combination in 2012
- Phys.Rev.D 88, 052014 (2013): properties of $H \rightarrow b\bar{b}$ from all channel update in July 2013



Significant excess over background only hypothesis:

- Analysis using both Log Likelihood Ratio (LLR) and Bayesian posterior cross section measurement
- $\sigma(WH + ZH) \times BR(H \rightarrow b\bar{b}) = 0.19 \pm 0.09 \text{ pb}$ (SM exp. 0.12 ± 0.01)
 \Rightarrow Measurement of $H \rightarrow b\bar{b}$ competitive with LHC

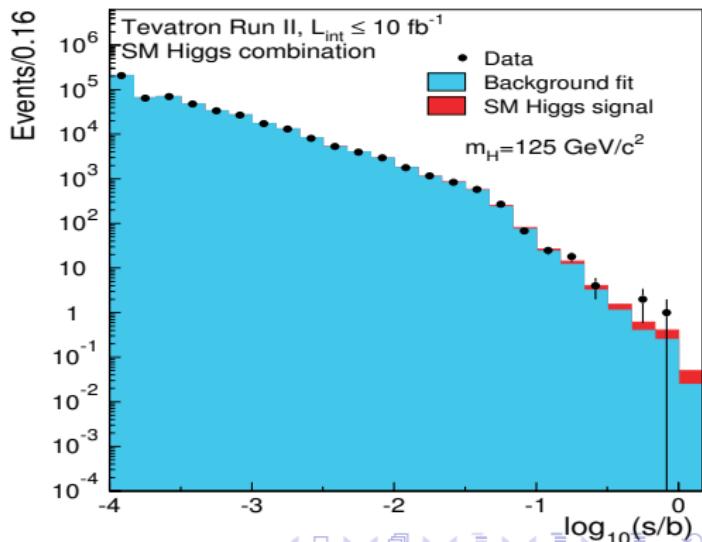
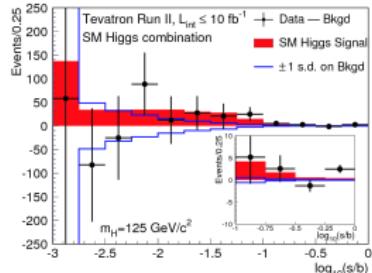
Tevatron Combination for All Analysis Channels

Next step \Rightarrow analyze SM Higgs from combination of all analysis channels, $> 100!$

- $H \rightarrow WW$ and $H \rightarrow b\bar{b}$ are the most important, but also $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$
- SM Higgs hypothesis testing is possible only looking at all the predicted decay modes
- Measure parameter of new particle: [Summer 2013 Results](#)

The global picture:

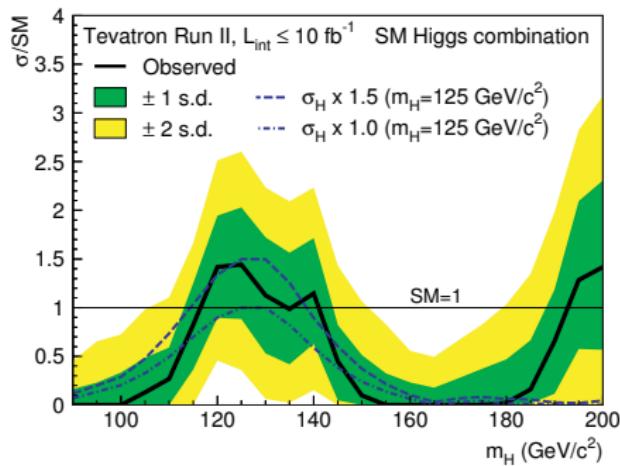
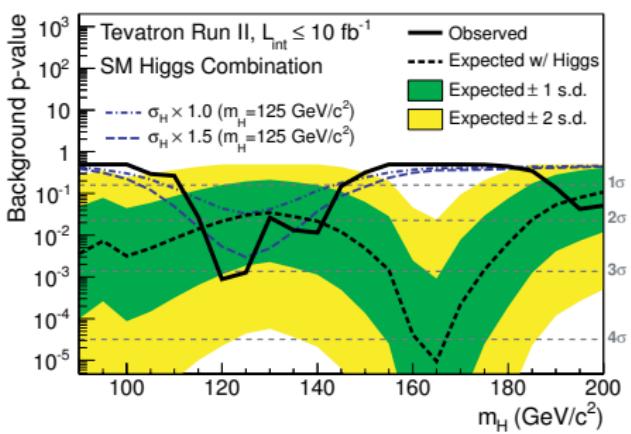
- Classification of all final discriminants in s/b bins
- Preserve importance of each data event
- $\log_{10}(s/b)$ shows agreement over 5 orders of magnitude



p – values and Cross Section

The full Tevatron combination results:

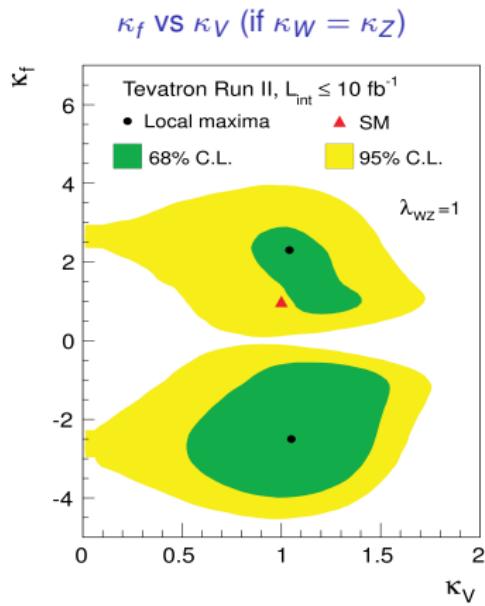
- Analysis of each channel discriminant with combined likelihood
- p -value 3.0σ (local) at $m_H = 125 \text{ GeV}/c^2$ (1.9 expected)
- $\mu = \sigma_{obs}/\sigma_{SM} = 1.44^{+0.59}_{-0.56}$ at $m_H = 125 \text{ GeV}/c^2$
- Consistent cross section between channels and with SM expectation



Higgs Coupling Measurements

- Most sensitive Higgs production and decay modes via W , Z , b -quark
- Extract coupling deviations from SM prediction from per-channel signal rates
- Assumptions: $m_H = 125 \text{ GeV}/c^2$, negligible width, $CP\ 0^+$, no invisible decay

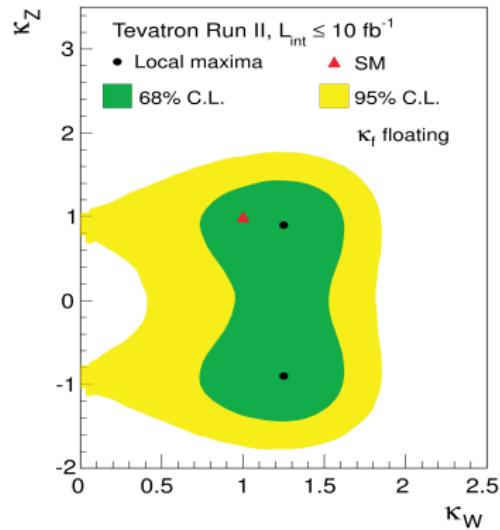
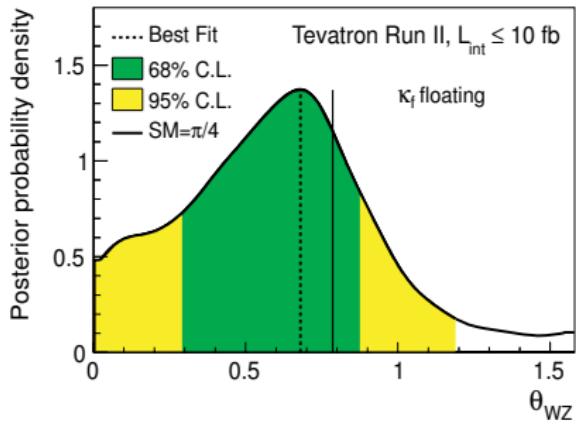
- κ_f fermion couplings scale
- κ_V boson coupling scale (if $\kappa_Z \equiv \kappa_W$)
- Examples:
 - $\Gamma_{b\bar{b}} \propto \kappa_f^2$, $\Gamma_{\tau\bar{\tau}} \propto \kappa_f^2$, $\Gamma_{ZZ} \propto \kappa_V^2$
 - $\Gamma_{WW} \propto R\kappa_V^2$ (with $R = \kappa_W/\kappa_Z$)
- Preserve unitary in BR:
es. $\Gamma_{\gamma\gamma} \propto (1.28\kappa_f - 0.281\kappa_V)^2$
- Study of coupling multiplicative parameters with 1-dim and 2-dim (shown) Bayesian posteriors



Vector Boson Couplings: κ_W vs κ_Z

Separate measurement of κ_Z vs κ_W

- κ_f is marginalized
- 95% C.L. exclusion of no-Higgs hypothesis: $(\kappa_Z, \kappa_W) = (0, 0)$
- 2-dim best fit:
 $\Rightarrow (\kappa_Z, \kappa_W) = (1.25, \pm 0.90)$



Test of $SU(2)$ custodial symmetry:

- by measuring $\lambda_{WZ} = \kappa_W / \kappa_Z$
- $\theta_{WZ} = \tan^{-1}(\kappa_Z / \kappa_W) = \tan^{-1}(1 / \lambda_{WZ})$
- $\theta_{WZ} = 0.68^{+0.21}_{-0.41} \Rightarrow \lambda_{WZ} = 1.24^{+2.34}_{-0.42}$

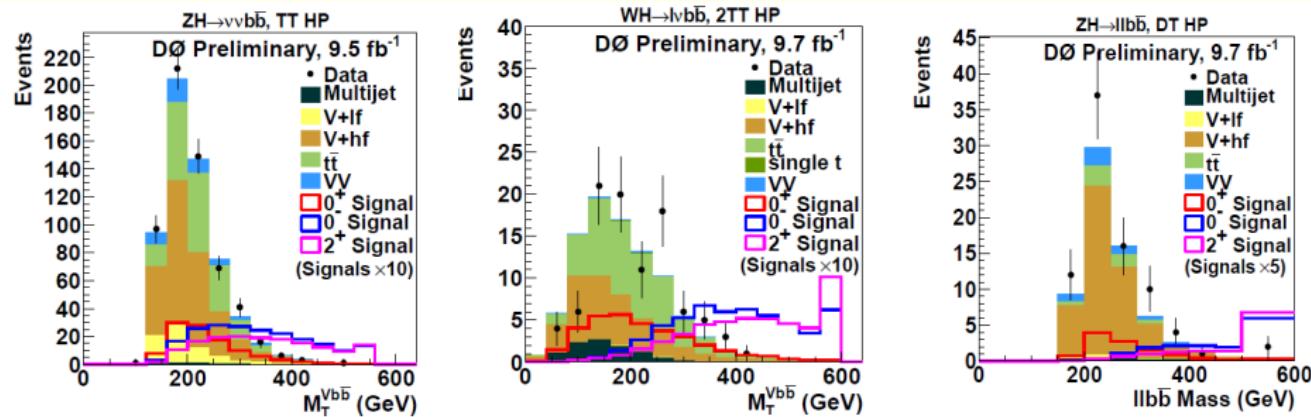


Additional Properties: Spin and Parity

- VH production processes differ depending on J^P assignment
- Kinematic differences from behaviors at production threshold, if $\beta = 2p/\sqrt{s}$:
- 0^+ : S-wave production, $\sigma \propto \beta$ near threshold
- 0^- : P-wave production, $\sigma \propto \beta^3$ near threshold
- 2^+ : D-wave dominates for graviton-like coupling, $\sigma \propto \beta^5$

cf. Ellis, et al., JHEP 1211, 134 (2012),
and Miller, et al., PLB 505, 149, (2001)

Probe Higgs J^P with VH total mass variables \Rightarrow background discrimination better than for 0^+ :

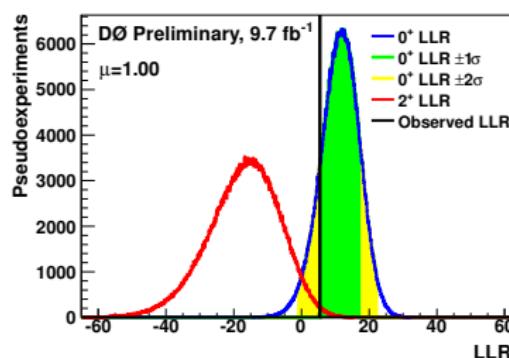
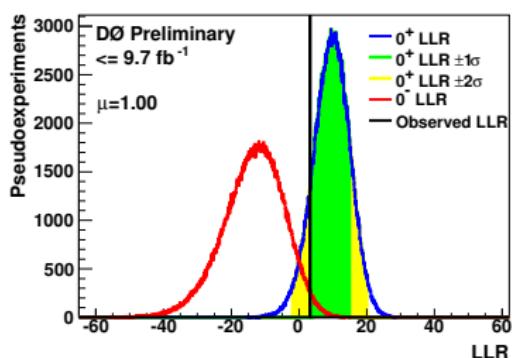


- 2^+ result Summer 2013: [D0 Note 6387](#)
- 0^- recent result (Autumn 2013): [D0 Note 6406](#)



Results of Spin and Parity Analysis

- Known m_H used in analysis optimization:
⇒ selection of High/Low purity regions in reconstructed mass
- LLR test statistics used to distinguish two hypothesis with CL_s :
⇒ H1 (Test): background plus 0^- or 2^+ Higgs signal
⇒ H0 (Null): background plus 0^+ Higgs signal
- Two scenarios: SM like $\sigma_{VH} \times BR(b\bar{b})$ (shown), or D0 measured rate ($\mu = 1.23$)

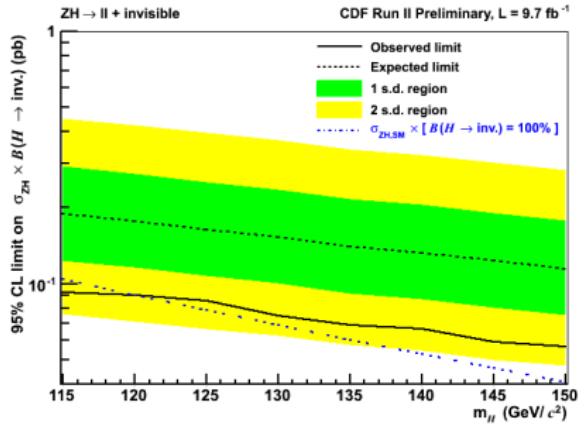
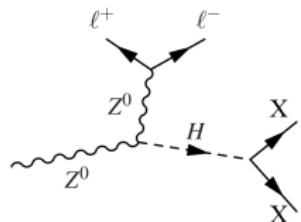


Exclusions results:

- 0^- model excluded at $> 97.9\% \text{ C.L.}$ ($2.3\sigma \text{ obs}, 3.1\sigma \text{ exp}$)
- 2^+ model excluded at $> 99.9\% \text{ C.L.}$ ($2.4\sigma \text{ obs}, 3.2\sigma \text{ exp}$)
- Very good sensitivity but model dependent assumptions

Invisible Higgs

- New CDF analysis testing exotic Higgs models: [CDF Note 11068](#)
- First measurement at the Tevatron probing $\sigma_{ZH} \times BR(H \rightarrow \text{invisible})$
- If kinematically accessible, decays to heavy unknown and weakly interacting particles are likely because of Yukawa coupling ($\propto m$) to Higgs
- $ZH \rightarrow \ell\ell + \cancel{E}_T$: $82 < M_{\ell\ell} < 100 \text{ GeV}/c^2$, clean signature
- Bayesian 95% C.L. exclude 100% $BR(H \rightarrow \text{invisible})$ for $m_H < 120 \text{ GeV}/c^2$



Summary and Prospects

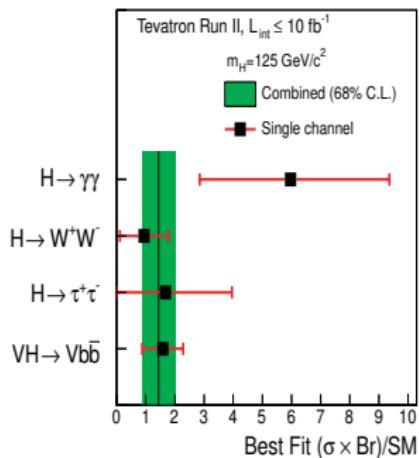
Summary of Tevatron Run II Higgs studies:

- High and low Higgs mass analysis channels based on full dataset completed and published
- Data show a consistent picture of the SM Higgs:
 - ⇒ p-value 3.0σ (local) at $m_H = 125 \text{ GeV}/c^2$
 - ⇒ $\mu = \sigma_{obs}/\sigma_{SM} = 1.44^{+0.59}_{-0.56}$ at $m_H = 125 \text{ GeV}/c^2$

Recent results and work in progress:

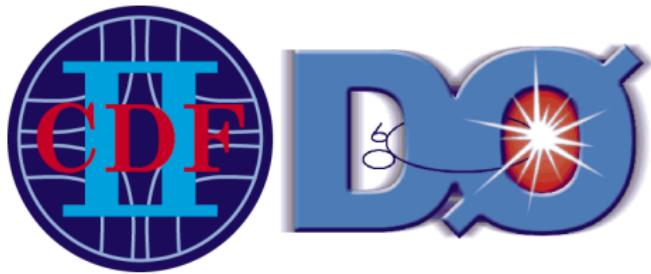
- $VH \rightarrow b\bar{b}$ datasets re-analyzed by D0 collaboration extracting spin and CP measurements:
 - ⇒ $J^P = 0^+$ nature of the new particle are favored
 - ⇒ $J^P = 2^+, 0^-$ models rejected at $> 97\%$ C.L.
 - ⇒ Tevatron combination is in progress
- Exotic Higgs properties:
 - ⇒ new analysis $H \rightarrow \text{invisible}$

$(\sigma \times BR)/SM$ for decay channel:



Tevatron analyses still provide good sensitivity to $H \rightarrow b\bar{b}$ final state and Higgs properties studies are often complementary to LHC

Thanks for Your Attention



Back Up Slides

All Channels and Analysis Details References

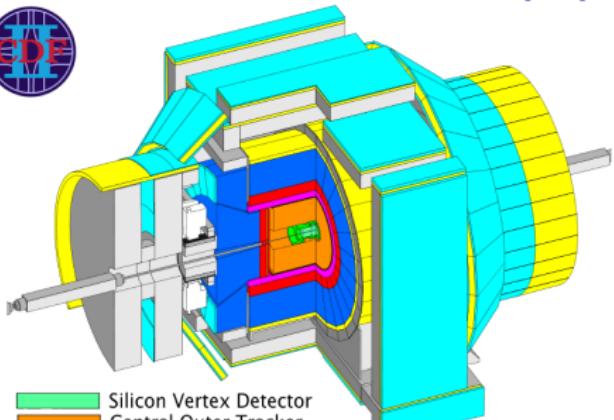
Channel		Luminosity (fb ⁻¹)	m_H range (GeV/c ²)
$WH \rightarrow \ell\nu b\bar{b}$ 2-jet channels $4 \times (5b\text{-tag categories})$		9.45	90–150
$WH \rightarrow \ell\nu b\bar{b}$ 3-jet channels $3 \times (2b\text{-tag categories})$		9.45	90–150
$ZH \rightarrow \nu\bar{\nu} b\bar{b}$ (3b-tag categories)		9.45	90–150
$ZH \rightarrow \ell^+\ell^- b\bar{b}$ 2-jet channels $2 \times (4b\text{-tag categories})$	$H \rightarrow b\bar{b}$	9.45	90–150
$ZH \rightarrow \ell^+\ell^- b\bar{b}$ 3-jet channels $2 \times (4b\text{-tag categories})$		9.45	90–150
$WH + ZH \rightarrow jj b\bar{b}$ (2b-tag categories)		9.45	100–150
$t\bar{t}H \rightarrow W^+ bW^- b\bar{b}\bar{b}$ (4 jets, 5 jets, ≥ 6 jets) $\times (5b\text{-tag categories})$		9.45	100–150
$H \rightarrow W^+W^-$ $2 \times (0\text{ jets}) + 2 \times (1\text{ jet}) + 1 \times (\geq 2\text{ jets}) + 1 \times (\text{low-}m_{\ell\ell})$		9.7	110–200
$H \rightarrow W^+W^-$ ($e\text{-}\tau_{\text{had}}$) + ($\mu\text{-}\tau_{\text{had}}$)		9.7	130–200
$WH \rightarrow WW^+W^-$ (same-sign leptons) + (trileptons)	$H \rightarrow W^+W^-$	9.7	110–200
$WH \rightarrow WW^+W^-$ (trileptons with $1\tau_{\text{had}}$)		9.7	130–200
$ZH \rightarrow ZW^+W^-$ (trileptons with 1 jet, ≥ 2 jets)		9.7	110–200
$H \rightarrow \tau^+\tau^-$ (1 jet) + (≥ 2 jets)	$H \rightarrow \tau^+\tau^-$	6.0	100–150
$H \rightarrow \gamma\gamma$ $1 \times (0\text{ jet}) + 1 \times (\geq 1\text{ jet}) + 3 \times (\text{all jets})$	$H \rightarrow \gamma\gamma$	10.0	100–150
$H \rightarrow ZZ$ (four leptons)	$H \rightarrow ZZ$	9.7	120–200



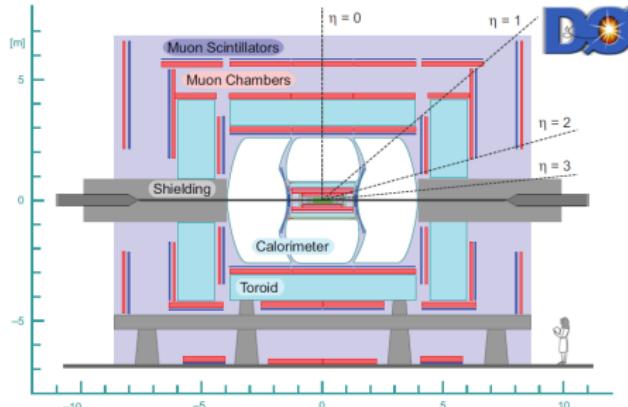
The CDF and D0 Experiments



Multipurpose detectors:



- █ Silicon Vertex Detector
- █ Central Outer Tracker
- █ 1.4 T Superconducting Solenoid
- █ EM Calorimeter
- █ Hadron Calorimeter
- █ Muon Counters/Chambers



Silicon ($|\eta| < 2.5$, $r \simeq 20$ cm)
 Drift cell ($|\eta| < 1.1$, $r \simeq 130$ cm)

Pb/Fe/Scintillators ($|\eta| < 3.6$)

Drift/Scintillators ($|\eta| < 1.5$)

**Inner Tracker
Outer Tracker**

Calorimeters

Muon Chambers

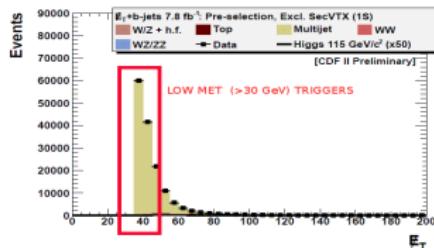
Silicon ($|\eta| < 3.0$, $r \simeq 10$ cm)
 Fiber ($|\eta| < 1.7$, $r \simeq 50$ cm)

LAr/U ($|\eta| < 4.0$)

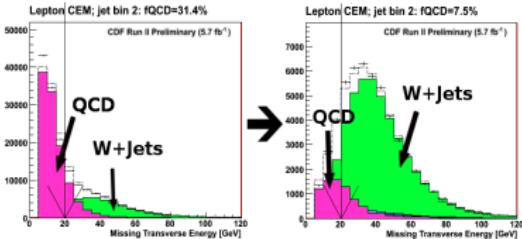
Drift/Scintillators $|\eta| < 2.0$

Analysis Improvement Examples

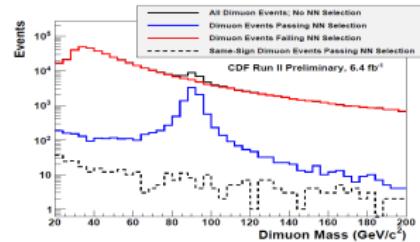
Low trigger thresholds (multi-dim. turn-on model):



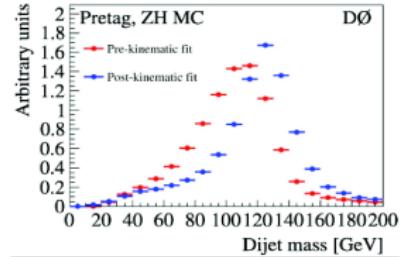
Variety of MJ-rejection techniques (here cut on SVM):



Lepton ID with NN selection:

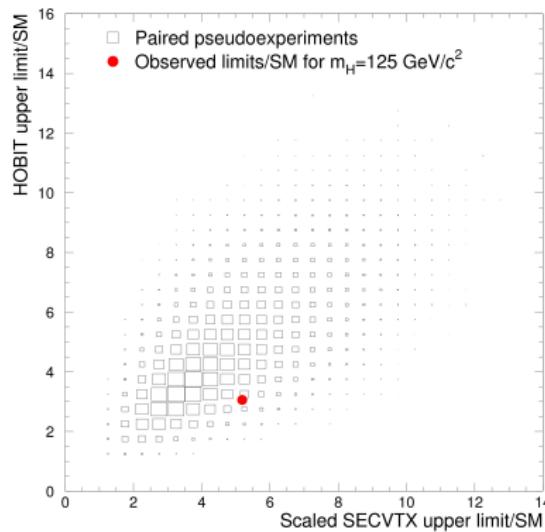


$Z \rightarrow \ell\ell$ kinematic fit to improve M_{jj} resolution:



CDF $ZH \rightarrow \nu\nu + HF$ Update

- 2012 result documented in Phys. Rev. Lett. 109, 111805 (2012), Updated 2013 result documented in Phys. Rev. D 87, 052008 (2013)
- Different b-tagging and, therefore, different signal region categorization: new result more sensitive but with lower observed limit
- Fluctuation possible with 7% probability tested with P.E.

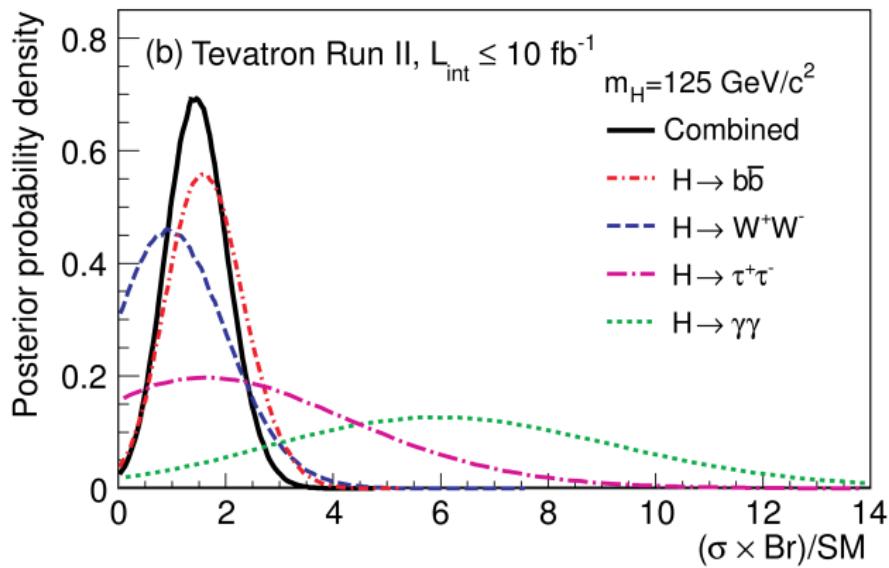


Two-sided p-value by calculating the conditional probability of obtaining a HOBIT result that is as or more discrepant than what we observe, given the S-J reanalysis observed limit

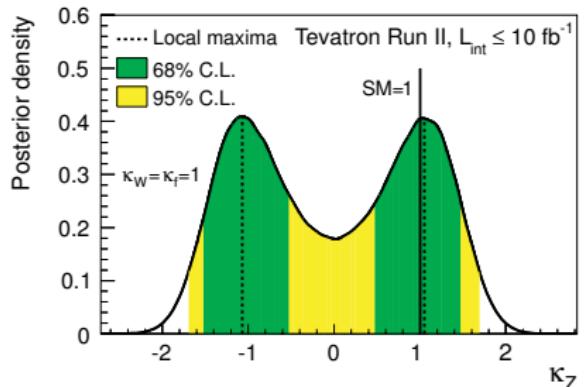
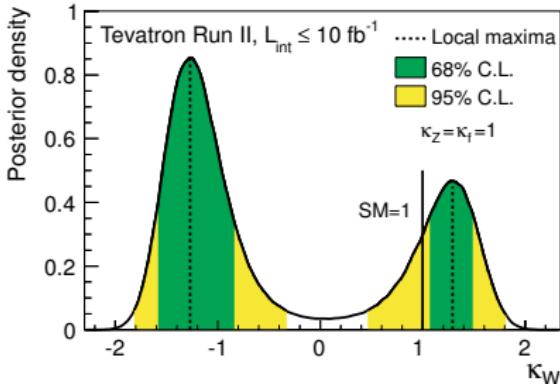
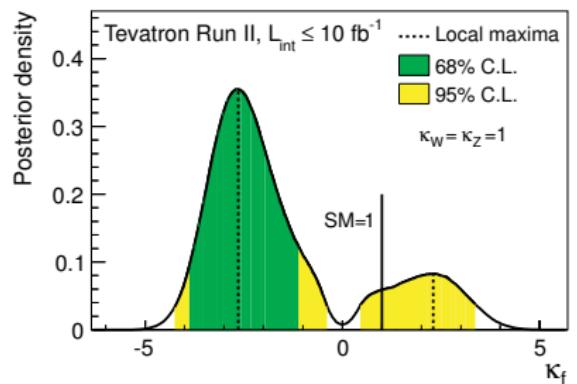
SM Higgs Compatibility Between Final States



$(\sigma_H \times BR)/SM$ in different final states:



1-Dim κ_f , κ_W , and κ_Z



Spin Exclusions Using D0 Measured SM Higgs Signal Strength

